THE OLDEST EARTH AND MOON ROCKS. Dianne J. Taylor, T. Mark Harrison, Kevin D. McKeegan and Edward D. Young. Dept. of Earth and Space Sciences & IGPP, UCLA, Los Angeles, CA, 90095, dtaylor@ess.ucla.edu

Introduction: One of the overarching themes of NASA's new lunar science roadmap is development of a coherent understanding of the origin and evolution of the Earth-Moon system [1]. Our research has focused on deciphering the Moon's earliest history and processes by using lunar zircons as both high resolution monitors of planetary differentiation and as a nano-scale record of the lunar cataclysm. We further propose experiments focusing on lunar zircons to search for >4 Ga terrestrial material on the Moon and to clarify the origin of the Earth-Moon system.

Lunar zircons as high resolution monitors of planetary differentiation: While it is generally agreed that the Moon began with a molten outer layer (referred to as the lunar magma ocean, or LMO [2,3]), it is still not known with certainty how long it took this region to crystallize and differentiate. This timing of lunar differentiation does not represent just another point in time in solar system history, but addresses issues of evolution pertaining to all the terrestrial planets, as it is now thought that many other solar system bodies (e.g. Earth, Mars, Vesta) experienced a global magma ocean period early in their history [4].

Presently, the Moon is the only accessible body in the solar system that preserves the rocks and geological structures formed between 4.5 and 4.4 Ga. We have studied zircons from saw cuttings of three Apollo 14 polymict breccias (14304, 14305 and 14321). These rocks are very high in the incompatible-trace-elements potassium (K), rare earth elements (REE) and phosphorus (P), indicating that their source magmas sampled a highly differentiated region of the lunar mantle referred to as the KREEP source region. The KREEP source was the final portion of the LMO to crystallize [5], and as such an age for isotopic closure of this source region would establish an upper bound for the duration of the LMO.

Coupled U-Pb and Lu-Hf measurements of these lunar zircons using secondary ion mass spectrometry (SIMS) and laser ablation inductively coupled mass spectrometry (LA-ICPMS) reveal a range of ages from 4.0 to 4.35 Ga along with highly subchondritic $^{176}Hf/^{177}Hf$ isotopic compositions, suggesting separation of the KREEP source, and thus crystallization of the lunar magma ocean, by ~4.50 Ga to no later than 4.44 Ga, within approximately 60 million years of solar system formation [6].

These results suggest that our understanding of the timing and mechanisms of lunar differentiation could be greatly enhanced using the outstanding qualities of zircon (and perhaps zirconalite) as both a chronometer and containment device for isotopic tracer information. However, with few exceptions, zircon is in low abundance in lunar rocks. Thus the prospect of returning to the Moon for additional focused sampling (and possible pre-concentration of zircon in situ) opens up the prospect of a variety of high resolution isotopic investigations of lunar differentiation processes. We propose an analysis campaign to extend Lu-Hf zircon measurements beyond the single landing site we have examined (Apollo 14) to include true lunar highland rocks and lunar meteorites. A feasibility study indicates that the UCLA NEPTUNE LA-ICPMS system is well-suited to these analyses [7].

Nature of the lunar cataclysm: An unexploited impact record for the Earth-Moon system is U-Th-Pb ion microprobe depth profiling of >4 Ga lunar zircons. This ultra-high spatial resolution technique probes the age and origin of nano-scale features in individual crystals that can record episodes of zircon growth or disturbance. Preliminary results [8] reveal growth zones in >4 Ga terrestrial zircons that are interpreted as evidence for a ~3.9 Ga thermal/crystallization event, coterminous with several large basin-forming impacts (e.g. Nectaris) on the Moon. In addition to our archive of >3,000 Hadean zircons that can be exploited for this purpose, we have begun to examine our lunar zircon samples for nano-scale evidence of ca. 3.9 Ga events.

Oxygen isotopes and the origin of the Earth-Moon system: Current theories for planetary accretion indicate that during growth of planetary embryos (Moon-sized bodies, e.g., [9]), $\Delta^{17}O$ signatures of planetesimals are highly variable but the meaning of these departures from terrestrial oxygen isotope reservoirs with respect to the structure and dynamics of the inner solar system is unclear. More to the point, we ask what the coincidence of Earth and Moon $\Delta^{17}O$ values [10] is in terms of the origin of the Earth-Moon system? The latter is less obvious than it might seem in view of the existence of another group of seemingly unrelated rocks, the enstatite chondrites (e-chondrites), the majority of which possess $\Delta^{17}O$ indistinguishable from Earth and Moon at the highest analytical precision. Most workers agree that the identical $\Delta^{17}O$ among enstatite chondrites and Earth/Moon is *not* evidence that enstatite chondrites once belonged to the Earth-Moon system, making less persuasive the opposite conclusion that identical $\Delta^{17}O$ among Earth and Moon *requires* thorough mixing of the oxygen comprising both bodies (e.g. [11]). Conversely, new data reveal at least two outlier e-chondrites with measurably more positive $\Delta^{17}O$ values than terrestrial, raising the possibility that new analyses of ancient Earth and Moon might yield surprises as well. For example, and by analogy with the enstatite chondrites, is it possible that distinct oxygen reservoirs (manifest as distinct $\Delta^{17}O$ values) persisted on earliest Moon and Earth due to late accretion? We propose that a search for oxygen isotope anomalies among the most ancient materials from Earth and Moon (e.g., zircons) might help answer questions about the final assembly of these bodies.

Discovery of >4 Ga terrestrial rocks on the Moon: Given the high Hadean terrestrial impact flux and locally quiescent, post-4.35 Ga thermal conditions in the lunar near-surface, a return to the Moon offers the prospect of discovering what we have not yet found on Earth: >4 Ga terrestrial rocks. The probability of encountering terrestrial materials during lunar sampling is perhaps as high as $1{:}10^5$ [12,13] and should guide both our use of the current inventory of lunar specimens and future sampling strategies. The importance of having even microscopic rock samples of Hadean Earth cannot be overemphasized. Specifically, zircons obtained from the Moon which have oxygen isotope compositions or Ti-temperatures [14] indicative of terrestrial continental crust could potentially provide unique constraints on early Earth history.

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